

# A HIGHLY DOPPLER BLUESHIFTED Fe-K EMISSION LINE IN THE HIGH-REDSHIFT QSO PKS 2149–306

T. Yaqoob<sup>1,2</sup>, I. M. George,<sup>1,2</sup> K. Nandra<sup>1,2</sup>, T. J. Turner<sup>1,3</sup>, S. Zobair<sup>1</sup>, P. J. Serlemitsos<sup>1</sup>

*Submitted 2 July 1999 for publication in Astrophysical Journal Letters*

Received \_\_\_\_\_; accepted Accepted 9/2/99

---

<sup>1</sup>Laboratory for High Energy Astrophysics, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA.

<sup>2</sup>Universities Space Research Association

<sup>3</sup>University of Maryland, Baltimore County.

## ABSTRACT

We report the results from an *ASCA* observation of the high-luminosity, radio-loud quasar PKS 2149–306 (redshift 2.345), covering the  $\sim 1.7 - 30$  keV band in the quasar-frame. We find the source to have a luminosity  $\sim 6 \times 10^{47}$  ergs s $^{-1}$  in the 2–10 keV band (quasar frame). We detect an emission line centered at  $\sim 17$  keV in the quasar frame. Line emission at this energy has not been observed in any other active galaxy or quasar to date. We present evidence rejecting the possibility that this line is the result of instrumental artifacts, or a serendipitous source. The most likely explanation is blueshifted Fe-K emission (the equivalent width is  $EW \sim 300 \pm 200$  eV, quasar frame). Bulk velocities of the order of  $0.75c$  are implied by the data. We show that Fe-K line photons originating in an accretion disk and Compton-scattering off a leptonic jet aligned along the disk axis can account for the emission line. Curiously, if the emission-line feature recently discovered in another quasar (PKS 0637–752,  $z = 0.654$ ) at 1.6 keV in the quasar frame, is due to blueshifted OVII emission, the Doppler blueshifting factor in both quasars is similar ( $\sim 2.7 - 2.8$ ).

*Subject headings:* galaxies: active – quasars: emission lines – quasars: individual: PKS 2149–306 , PKS 0637–752 – X-rays: galaxies

## 1. INTRODUCTION

X-ray emission lines are powerful diagnostics of the physical conditions and structure in active galactic nuclei (AGNs). The picture emerging from many X-ray studies of AGNs over the last couple of decades is that emission features in the X-ray spectra become scarce in AGNs with 2–10 keV intrinsic luminosity exceeding  $\sim 10^{45}$  ergs s $^{-1}$ . This trend is discussed at length in Nandra *et al.* (1996, 1997a) and Reeves *et al.* (1997; and references therein). The transition to a featureless X-ray power-law continuum in the vast majority of the high luminosity AGNs is not fully understood, but may be related to the complete ionization of matter responsible for emission-line features and/or beaming of the X-ray continuum swamping out emission-line features. Any emission features observed in type 1 AGN are almost always Fe-K lines, although there are a handful of reports of other features (George, Turner, and Netzer 1995; Fiore *et al.* 1998; Turner, George and Nandra 1998), all in low-luminosity AGNs. However, Yaqoob *et al.* (1998) reported an emission line in the high-luminosity radio-loud quasar PKS 0637–75 ( $z = 0.654$ ,  $L[2 - 10 \text{ keV}] \sim 10^{46}$  ergs s $^{-1}$ ). The line energy was 1.6 keV in the rest-frame and was interpreted as highly blueshifted OVII.

In this paper we report another X-ray emission-line feature at an unexpected energy, in the radio-loud quasar PKS 2149–306 ( $z = 2.345$ ). With  $L[2 - 10 \text{ keV}] > 10^{47}$  ergs s $^{-1}$ , this makes PKS 2149–306 the most luminous and highest redshift AGN in which an X-ray emission line detection has been claimed. The *ASCA* (*Advanced Satellite for Cosmology and Astrophysics*; Tanaka, Inoue and Holt 1994) observation of PKS 2149–306 reported here has also been studied by Siebert *et al.* (1996) and Cappi *et al.* (1997). The emission line is visible by eye in their work, but went unnoticed because it is common practice to only search for emission lines at energies one would expect.

## 2. THE ASCA DATA

ASCA observed PKS 2149–306 on 1994 October 26–27 for a duration of  $\sim 50$  ks. The reader is referred to Tanaka *et al.* (1994) for details of the instrumentation aboard ASCA. The two Solid State Imaging Spectrometers (SIS), hereafter SIS0 and SIS1, with a bandpass of  $\sim 0.5 - 10$  keV, were operated in 1-CCD FAINT and BRIGHT modes. The two Gas Imaging Scintillators (GIS), hereafter GIS2 and GIS3, with a bandpass of  $\sim 0.7 - 10$  keV, were operated in standard PH mode. The data reduction procedures follow exactly those described in Yaqoob *et al.* (1998) and the reader is referred to that paper for the details of the data reduction, relevant calibration, other systematic uncertainties, and screening criteria. Screening resulted in net ‘good’ exposure times in the range  $\sim 19.4$ – $19.9$  ks for the four instruments.

Images were accumulated from the screened data and they were examined for possible nearby contaminating sources. No such sources were detected. Source events were extracted from circular regions with radii of  $4'$  for the SIS and  $6'$  for the GIS. Background events were extracted from off-source regions. As a check, background spectra were also made from a 1-CCD mode blank-sky observation which resulted from the non-detection of the quasar IRAS 15307+3252 (observed 1994 July). These background data were subject to identical selection criteria and used to check the invariance of the spectral results for PKS 2149–306 described below. The count rates in the accumulated background-subtracted spectra for PKS 2149–306 ranged from  $\sim 0.17$ – $0.30$  ct/s. Spectra were binned to have a minimum of 20 counts per bin in order to utilize  $\chi^2$  as the fit statistic.

The ASCA lightcurves do not show significant variability, the highest excess variance (e.g. see Nandra *et al.* 1997b) we obtain is from SIS0 and has the value  $(6.9 \pm 3.7) \times 10^{-3}$  for 128 s bins. This is to be compared with  $0.111 \pm 0.005$  we obtain for the highly variable Seyfert 1 MCG –6–30–15 from a 4 day ASCA observation.

### 3. SPECTRAL FITTING RESULTS

We fitted spectra from the four *ASCA* instruments simultaneously in the range 0.5–10 keV with a simple power-law plus cold, neutral absorber model. A total of two interesting parameters were involved (the photon index,  $\Gamma$ , and column density,  $N_H$ ), plus four independent instrument normalizations. (The deviation of any of the four normalizations from their mean was less than 7%). The results are shown in Table 1. The best-fitting photon index,  $\Gamma = 1.54 \pm 0.05$ , is consistent with that reported by Siebert *et al.* (1996) and Cappi *et al.* (1997) and is rather flat. The column density,  $N_H$ , is at least a factor 3 higher than the Galactic value of  $2.12 \times 10^{20} \text{ cm}^{-2}$  obtained from Dickey and Lockman (1990). The instrument-averaged *observed* 0.5–2 keV and 2–10 keV fluxes are 3.6 and  $10.1 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1}$  respectively. The 2–10 keV luminosity in the source frame is  $5.8 \times 10^{47} \text{ ergs s}^{-1}$  ( $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$  and  $q_0 = 0$ ).

Although the above simple continuum model provides an adequate fit, inspection of the ratios of data to model (Figure 1) reveal a statistically significant (see below) ‘hump’ at  $\sim 5 \text{ keV}$  (observed frame) in both SIS0 and SIS1.

We repeated the four-instrument *ASCA* fits with the addition of a simple Gaussian to model the apparent emission-line feature. Three extra parameters were involved, namely the line center energy,  $E_c$ ; the Gaussian intrinsic width,  $\sigma$ , and the line intensity,  $I$ . *Note that we will refer to all three parameters, plus the equivalent width (EW), in the quasar frame.* Initially we allowed all three parameters to float but the line width was not constrained (the best fit giving  $\sigma \sim 1 \text{ keV}$  with only  $\Delta\chi^2 = 1.2$  relative to the case for a narrow line). The results for a narrow-line fit with  $\sigma$  fixed at 0.01 keV are given in Table 1. Note that the decrease in  $\chi^2$  compared to the model without an emission line is 10.3 for the addition of two free parameters so the line feature is detected at a confidence level greater than 99%. It is appropriate here to use a  $\Delta\chi^2 = 4.61$  criterion to derive 90%

confidence errors on the best-fitting line parameters since we want to know the bounds on  $E_c$  and EW, independently of  $\Gamma$  and  $N_H$  (e.g. see Yaqoob 1998). We obtain, approximately,  $E_c = 17.0 \pm 0.5$  keV and  $EW = 300 \pm 200$  eV. We also tried fitting SIS0 and SIS1 with a narrow line separately and obtained  $\Delta\chi^2 = 5.1$  and 6.8 respectively. From Figure 1 it appears that  $\Delta\chi^2$  should be higher for SIS0, not SIS1. However, these results are for a *narrow line*. The SIS0 data, which have the better statistical quality, prefer a somewhat broader feature. We also fitted a narrow line to the GIS2 plus GIS3 data only, this time with the energy fixed at 17 keV, and obtained a 90% ( $\Delta\chi^2 = 2.7$ ) upper limit on the intensity of  $6.2 \times 10^{-5}$  photons  $\text{cm}^{-2} \text{s}^{-1}$ , consistent with the intensity in Table 1. The feature is not obvious in the GIS; this is not surprising and it is quite common for weak Fe-K lines in AGN to be detected in the SIS but not the GIS. The GIS count rates are a factor 1.5–2 lower than the SIS (due to larger off-axis angles) and the energy resolution is a factor  $\sim 4$  times worse. We also examined public archive data from a *BeppoSAX* observation of PKS 2149–306 performed in October 1997. No line was detected but the data do not rule it out. Again, the count rates (in the MECS) were much lower than SIS (a factor of  $\sim 6$  less) and the energy resolution worse by a factor of  $\sim 4$ .

#### 4. THE REALITY OF THE EMISSION-LINE FEATURE

Since an emission-line feature like that reported above has never before been observed in any AGN, we sought explanations which did not require the line to be intrinsic to the quasar.

Firstly, is it possible that some or all of the X-ray emission is due to another source? PKS 2149–306 is in the *ROSAT* All-Sky Survey Bright Source Catalog but no other X-ray source is found within 11 arcmin. However, the Cambridge APM shows up an extended source only 2 arcmin away, of similar optical magnitude. This source was not found in

either the SIMBAD or NED databases and remains a mystery. In case this latter source is absorbed but still contributing to the hard X-rays, we compared the PSF of the *ASCA* PKS 2149–306 data with the PSF for a bright point source (3C 273), and also with the PSF of an extended source (the cluster E0657–56, see Yaqoob 1999). The results are shown in Figure 2. The *ASCA* data are fully consistent with the X-ray emission from a single point source corresponding to PKS 2149–306. We also note the bright cluster  $\sim 40$  arcmin away, Abell 3814, cannot be responsible for contamination of the *ASCA* data either. Besides, its redshift is 0.118 so the Fe-K line complex would be observed around 6 keV, whereas we observe the emission line in PKS 2149–306 at  $\sim 5.1$  keV.

To demonstrate that the SIS calibration is not responsible we examined SIS data from an observation of the X-ray binary 4U 1957+11, performed  $\sim 4$  days after the PKS 2149–306 observation. Figure 3 shows the ratios of data to a simple power-law plus absorber model (both SIS0 and SIS1) fitted over the 2–10 keV range. It can be seen that no emission line feature at 5.1 keV is present in these data. We also made new SIS spectra for PKS 2149–306 artificially changing the gain by  $\pm 1\%$ . This did not change the results - the emission line was still present, with insignificant effect on the line parameters. There is the remaining possibility that some other, unknown instrumental artifact, occurring only during the PKS 2149 observation, was responsible for producing or mimicking an emission line. We consider this highly unlikely, however, particularly as the line is clearly detected in both SIS.

The emission line cannot be a background feature (for example from Galactic diffuse emission) because the background from nearby regions in the same field and at the observed energy of the emission line in the SIS lies at least a factor 20 below the on-source spectrum. Also, we repeated the spectral analysis using the alternative background spectra made from a blank field, as described in §2, and the results were confirmed to be robust to the

background used. It is unlikely that the emission line is produced in an intervening galaxy since that galaxy would have to be extremely bright for the emission line to be detectable above the quasar continuum, with a redshift of  $\sim 0.3$ . Such a galaxy would be bright enough that signatures in the optical would have been detected.

Finally, we can ask, what is the chance probability that a line-like feature is detected in *both* SIS0 and SIS1, due to random statistical fluctuations, if we examine a sample of high-redshift quasars? Suppose the quasar spectra have  $N$  energy bins. The probability of finding a *positive* fluctuation, relative to some continuum model, of more than  $2\sigma$  (i.e. about the level of detection in *each* SIS for PKS 2149–306 ), in one or more energy bins, in SIS0 say, is  $1 - [1 - p]^N$  where  $p = \int_{+2\sigma}^{\infty} \exp(-x^2/2\sigma^2) dx = 2.276 \times 10^{-2}$  (assuming a Gaussian distribution). Then the probability that the same feature is detected at more than  $2\sigma$  in SIS1, in the same energy bin is  $P = p(1 - [1 - p])^N$ . Note that the  $\sim 2\sigma$  detection in *each* SIS is consistent with the  $\sim 3\sigma$  net detection as indicated by the  $\Delta\chi^2$  from the spectral fits (see Table 1). We examined all quasars with  $z > 0.158$ , for which the ASCA data were public as of 1998, December 4. This amounted to 87 observations of 86 sources. Of these, only 31 datasets yielded spectra which were of sufficient quality to search for line-emission (specifically, we defined this so that the SIS0 spectrum had to be brighter than 0.05 ct/s). Assuming the highest value for the number of bins in each SIS spectrum ( $N = 155$ ) in order to get the most conservative estimate, we obtain  $P = 0.022$ . Thus, of the 31 datasets we expect less than one (0.69) to yield an emission-line in both SIS0 and SIS1 from random fluctuations alone. Then, for the 31 spectra, we measured the  $\Delta\chi^2$  resulting from inserting a narrow Gaussian emission line at 100 energies between 0.5 and 8 keV for each dataset, relative to a simple power-law plus Galactic absorption continuum model, fitted simultaneously to four instruments. We found four sources for which  $\Delta\chi^2 > 9$  (i.e. a detection significance of  $> 3\sigma$  for 1 interesting parameter). These were E1821+143 (see Yamashita *et al.* 1997), PG 1116+265 (see Nandra *et al.* 1996), PKS 0637–752 (see



Yaqoob *et al.* 1998), and PKS 2149–306. The probability of finding four such sources by chance is  $(31!/27!/4!)P^4(1 - P)^{27}$ , or 0.4%. Even without the two sources with highly probable bona-fide Fe-K lines, the probability is  $(29!/27!/2!)P^2(1 - P)^{27}$ , or 10.9%.

## 5. DISCUSSION

The most likely explanation for the detection of an emission line centered at  $\sim 17$  keV in the rest frame of the radio-loud quasar PKS 2149–306 ( $z = 2.345$ ) is blueshifted Fe-K emission (at a rest-energy in the range 6.4–6.97 keV). The Doppler factor (ratio of Lorentz-boosted energy to rest-energy),  $D = 2.42 - 2.65$  implies bulk-motion velocities of  $0.71c - 0.75c$  (head-on). Interpreting the emission line in PKS 2149–306 as highly blueshifted Fe-K carries with it some strong physical constraints with respect to its origin, in order to account for the large rest-frame equivalent width (EW) of  $(300 \pm 200 \text{ eV})$ .

The main problem is for the line-emitting material to present enough solid angle to the X-ray continuum source to produce sufficient line equivalent width, but not so much that the line becomes too broad. These conflicting requirements must be overcome by any model. For example, although a spherical distribution of optically-thick clouds (e.g. see Nandra and George 1994) could produce the necessary equivalent width with only a modestly small covering factor of  $\sim 3\%$  and infall with  $\beta \equiv v/c = 0.75$ , the fact that one must integrate over all line-of-sight angles would give a broad line profile stretching from  $\sim 2.4 - 17$  keV in the rest frame. (Infall, as opposed to outflow or a chaotic velocity field gives the largest boost to the equivalent width since the continuum as seen by the Fe atoms is maximally Lorentz-boosted, as well as the line emission).

Here we propose a possible model which overcomes the conflicting solid-angle requirements. We suppose that an Fe-K emission line is produced in an accretion disk, just

as thought to be the case for Seyfert 1 galaxies and some quasars with redshift lower than that of PKS 2149–306. Further, the line is assumed to be narrow (relative to the *ASCA* spectral resolution of  $\sim 150$  eV at Fe-K), like that observed in the high-luminosity quasar PG 1116+205 (i.e. not as broad as the Fe-K lines observed in Seyfert 1). Then, we invoke a leptonic jet aligned along the disk axis, with the leptons outflowing at  $\beta \sim 0.75$ . For the sake of argument, it is assumed that the observer's line of sight is aligned with the jet axis (it doesn't have to be exactly aligned). If the jet is very long compared to the disk radius then the requirement of a small solid angle is satisfied, (resulting in a line-profile which is not too broad, especially in view of the tightly constrained velocity field of the jet), and yet can potentially intercept most of the Fe-K line photons from the disk which escape parallel to the disk and jet axis. The disk photons will be Compton-scattered by the leptons in the jet and will be highly collimated along the jet axis since the line photons leaving the disk and intercepting the jet are strongly aligned along the disk/jet axis and the Doppler boosting by the jet favours forward scattering, the larger the Lorentz factor. This again ensures that the line does not become too broad. Now, both line and continuum photons will experience the same Doppler effects so the only factor contributing to an increase in the equivalent width (EW) of the line is the fact that the latter is defined as ratio of line to continuum *per unit energy* so the intrinsic EW ( $\equiv EW_0$ ) will be increased by a factor  $F \equiv Df[1 - \exp(-\tau)]$  where  $f$  is the fraction of the disk area blocked by the jet and  $\tau$  is the jet Thomson optical depth. Actually the optical depth will vary at different points along the jet so  $\tau$  represents the value averaged over all the interactions of the disk line-photons with the jet. In principle,  $EW_0$  could be as large  $\sim 300$  eV (as observed in Seyfert galaxies). This would imply  $F \sim 0.4$ ; on the other hand if  $EW_0$  is a few tens of eV (say, 50 eV),  $F \sim 2$ . Multiple scattering is not a problem because the velocity field is so narrow that multiply-scattered photons will appear as narrow (weaker) features at higher energies. Such a fine-tuning of  $\tau$  also may explain why the phenomenon is not commonly observed in other

quasars. This model also predicts that nothing unusual would be observed in the optical emission-line spectrum (and indeed this is the case, e.g. Wilkes 1986) if the BLR is situated much further from the central X-ray source than the disk-jet system.

We thank Andy Fabian and Rick Edelson for discussions on the results presented in this paper. We also thank an anonymous referee for helping to improve the paper. We thank the *ASCA* mission operations team at ISAS, Japan, and all the instrument teams for their dedication and hard work in making these *ASCA* observations possible. This research made use of the HEASARC archives at the Laboratory for High Energy Astrophysics, NASA/GSFC and the NASA/IPAC Extragalactic Database (NED) which is operated by JPL, CALTECH, under contract with NASA.

Table 1. Spectral Fits to PKS 2149–306

Parameter	No line	Narrow line
$\Gamma$	$1.54^{+0.05}_{-0.05}$	$1.56^{+0.05}_{-0.05}$
$N_H$ ( $10^{20}$ cm $^{-2}$ )	$7.0^{+2.3}_{-2.3}$	$7.5^{+2.4}_{-2.3}$
$\sigma$ (keV)		0.01 (FIXED)
$E_c$ (keV)		$17.00^{+0.52}_{-0.48}$
$I$		$4.5^{+3.1}_{-3.1}$
EW (eV)		$298^{+202}_{-205}$
$\chi^2$	585.6	575.3
degrees of freedom	578	576

Note. — The continuum model used is a simple power law plus absorber with the photon index,  $\Gamma$ , and column density,  $N_H$ , floating. The absorber is placed at  $z = 0$ . The emission line parameters are all referred to in the quasar frame ( $z = 2.345$ ); these are the intrinsic width,  $\sigma$ , the center energy,  $E_c$ , the intensity ( $10^{-5}$  photons cm $^{-2}$  s $^{-1}$ ), and the equivalent width (EW). Errors are 90% confidence for two interesting parameters ( $\Delta\chi^2 = 4.61$ ).

## REFERENCES

- Cappi, M., Matsuoka, M., Comastri, A., Brinkmann, W., Elvis, M., Palumbo, G. C., & Vignali, C. 1997, *ApJ*, 478, 492
- Dickey, J.M., & Lockman, F.J. 1990, *Ann. Rev. Ast. Astr.* 28, 215.
- Fiore, F., *et al.* 1998, *MNRAS*. 298, 103
- George, I.M., Turner, T.J., & Netzer, H. 1995, *ApJ*, 438, L67
- Nandra, K., & George, I.M. 1994, *MNRAS*, 268, 405
- Nandra, K., George, I.M., Mushotzky, R.F., Turner, T.J., & Yaqoob, T. 1997b, *ApJ*, 476, 70
- Nandra, K., George, I.M., Turner, T.J., & Fukazawa, Y. 1996, *ApJ*, 464, 165
- Nandra, K., Mushotzky, R.F., George, I.M., Turner, T.J., & Yaqoob, T. 1997a, *ApJ*, 488, 91
- Reeves, J.N., Turner, M.J.L., Ohashi, T., & Kii, T. 1997, *MNRAS*. 292, 468
- Siebert, J., Matsuoka, M., Brinkmann, W., Cappi, M., Mihara, T., & Takahashi, T. 1996, *A&A*. 307, 8
- Tanaka, Y., Inoue, H., & Holt, S.S. 1994, *PASJ*, 46, L37
- Turner, T.J., George, I.M., Nandra, K. 1998, *ApJ*, 508, 648
- Wilkes, B. J. 1986, *MNRAS*. 218, 331
- Yamashita, A., Matsumoto, C., Ishida, M., Inoue, H., Kii, T., Makishima, K., Takahashi, T., & Tashiro, M. 1997, *ApJ*, 486, 763
- Yaqoob, T. 1998, *ApJ*. 500, 893
- Yaqoob, T. 1999, *ApJ*, 511, L75

Yaqoob, T., George, I. M., Turner, T. J., Nandra, K., Ptak, A., & Serlemitsos, P. J. 1998, ApJ, 505, L87

## Figure Captions

### Figure 1

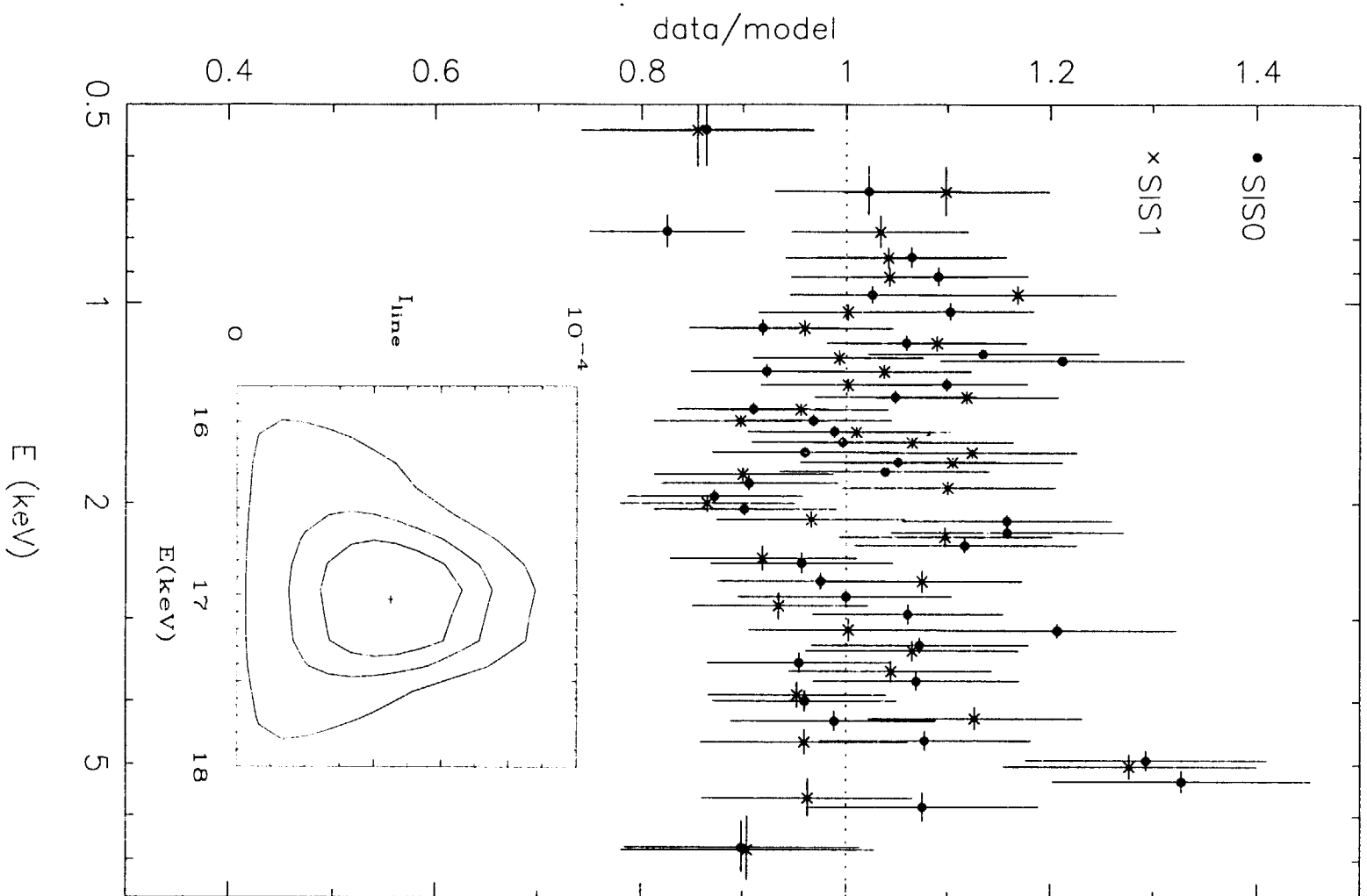
Ratio of the *ASCA* SIS spectral data for PKS 2149–306 ( $z = 2.345$ ) to the best-fitting power-law plus absorber model versus *observed* energy. Notice the significant residuals at  $\sim 5$  keV, corresponding to an emission line centered at  $\sim 17$  keV in the quasar frame (see text). The inset shows 68%, 90% and 99% confidence contours versus *rest-frame* energy, which result from fitting a Gaussian emission line to the residuals, corresponding to  $\Delta\chi^2 = 2.28, 4.61$ , and 9.21 respectively. The line intensity,  $I$ , is in units of photons  $\text{cm}^{-2} \text{s}^{-1}$ .

### Figure 2

The SIS0 Point Spread Function (PSF) for PKS 2149–306 (filled circles) compared with the the PSF for 3C 273, a point source (crosses and solid line). For comparison, also shown is the PSF for the cluster of galaxies 1E0657–56 at  $z = 0.296$  (open circles). Note that the off-axis angles for all three sources are similar so the PKS 2149–306 data are consistent with a point source centered on the quasar (see text).

### Figure 3

Ratio of SIS spectral data to best-fitting power-law plus absorber models for 4U 1957+11 and PKS 2149–306. The 4U 1957+11 data were taken just four days after the PKS 2149–306 data. Note that the vertical scale in both panels is identical. Thus, calibration uncertainties in the SIS cannot account for the emission-line feature seen in PKS 2149–306 (also see text).





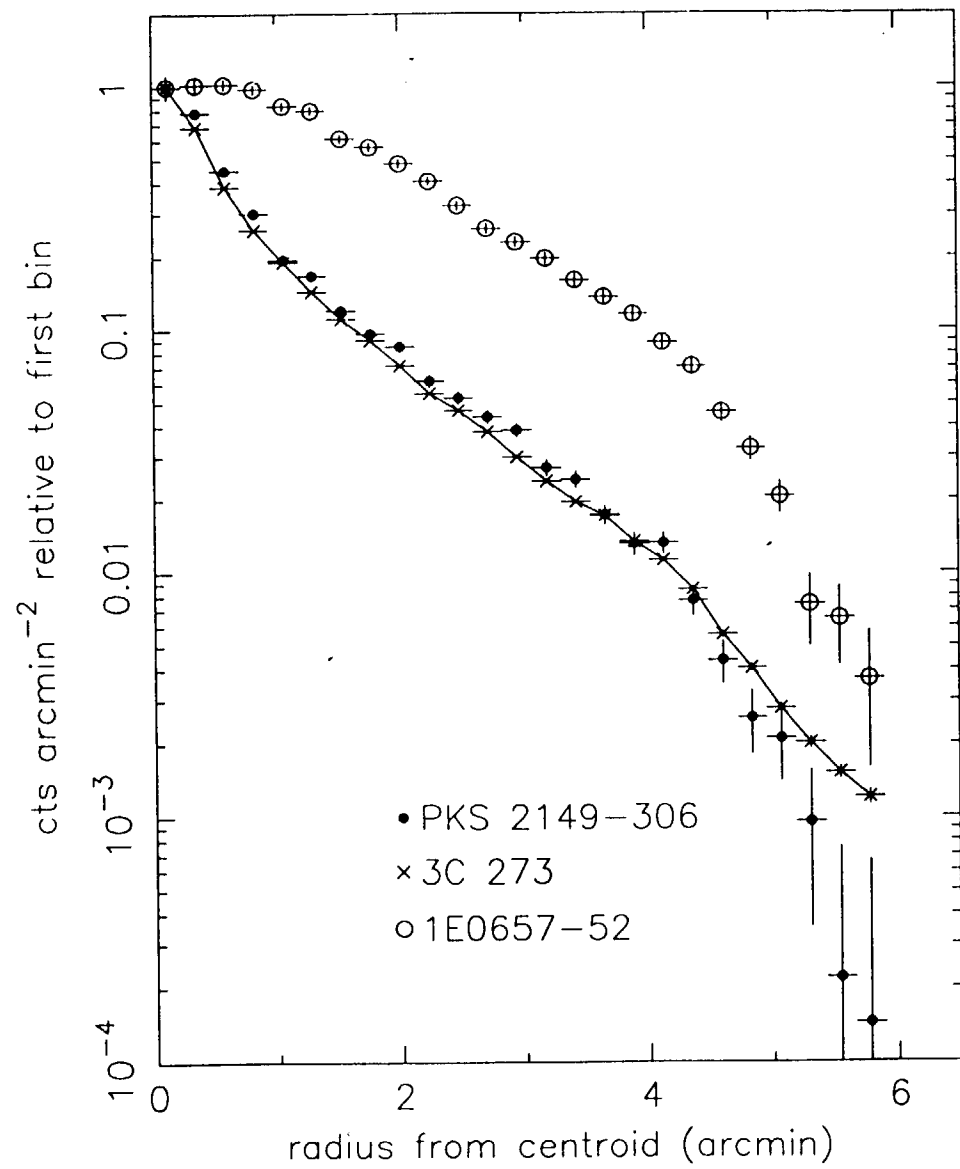


Fig. 2

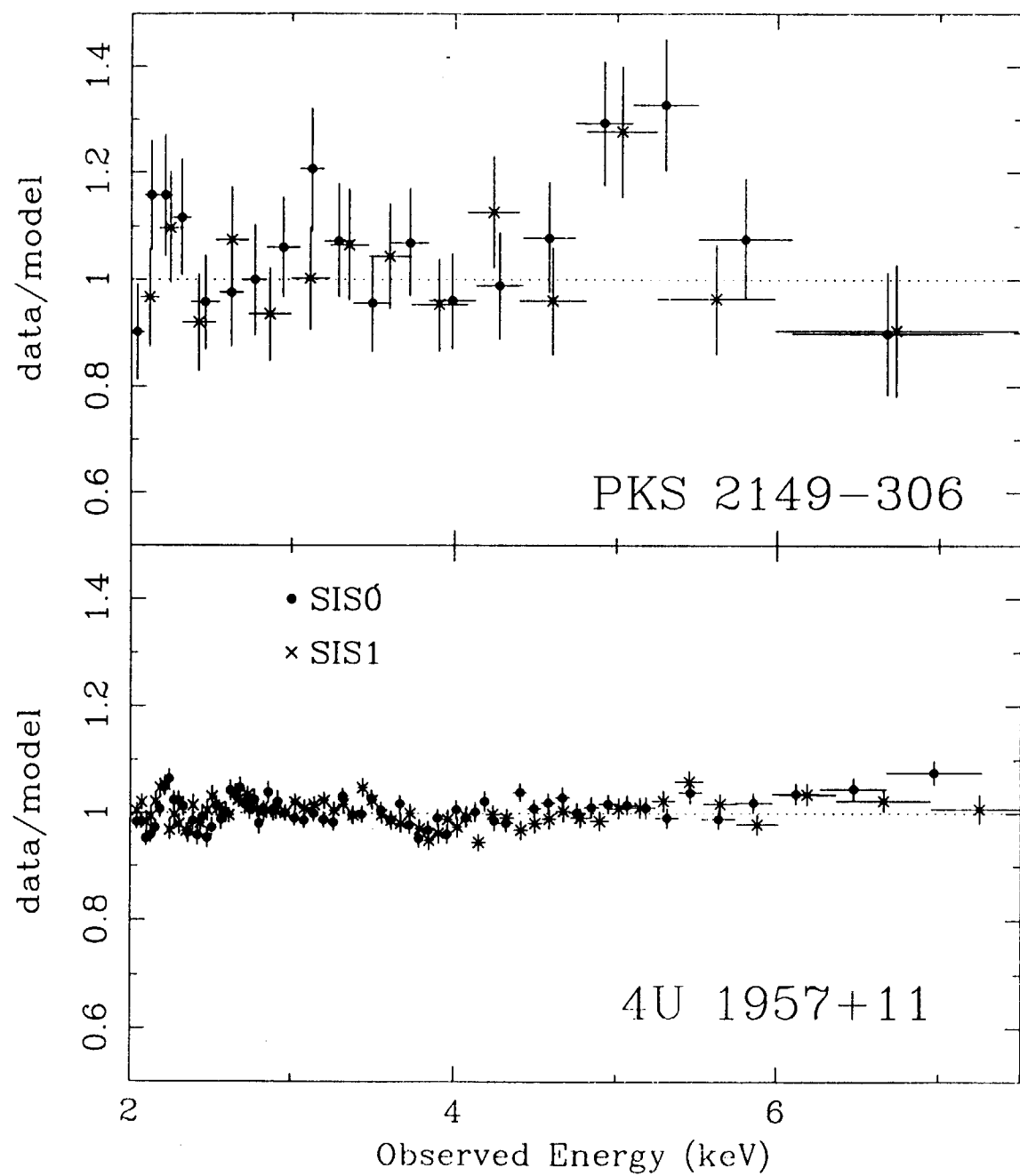


Fig. 3